

LACTIC ACID

Lactic acid (2-hydroxypropanoic acid, α -hydroxypropionic acid), $\text{CH}_3\text{CHOHCOOH}$, formula weight 90.08, the simplest hydroxy acid containing an asymmetric carbon atom, exists in two optically active forms and a racemic modification, all of which are water-soluble colorless liquids or low-melting solids in the pure state (1,3,13,19). This acid is widely distributed in nature. It is the primary acid constituent of sour milk (hence its name), and a normal constituent in the blood and muscle tissue of animals.

Lactic acid is one of the principal acidulants in food and beverage products. It is also used in deliming hides, in the tanning of leather, and in the acid dyeing of wool. Lactic acid esters (see p. 178) are useful as lacquer solvents, and small quantities are used directly in plastics. Lactic acid enters the pharmaceutical field as calcium lactate for calcium therapy; other salts such as sodium and potassium lactate, which are hygroscopic, have found use as glycerol substitutes (see p. 178) (15,18,19,24,31).

Most of the earlier studies of lactic acid were concerned with physiological phenomena or with stereochemistry and related fields. Scheele discovered lactic acid in sour milk in 1780. Many illustrious chemists, such as Liebig, Berzelius, Wurtz, Kekulé, Strecker, and Wislicenus, have contributed to the historical and classical development of our knowledge of lactic acid. The early work aimed at identifying and characterizing the different lactic acids (dextro, levo, and racemic forms) was handicapped by their unfavorable physical properties. Being extremely soluble in both water and water-miscible organic solvents but insoluble in other organic solvents, the acids were obtained only with considerable difficulty as low-melting, hygroscopic, and generally ill-defined solids.

Ultimately, however, the optically active forms of lactic acid and many of its derivatives were prepared in pure condition and subjected to intensive study. These investigations were important in developing the chemistry of lactic acid as well as basic theories of stereochemistry.

Discoveries in the chemistry of lactic acid were followed by commercial manufacture and use of this readily prepared material. The manufacture and chief uses for lactic acid were developed by Americans; the industry was well established in the U.S. before the manufacture of lactic acid was undertaken in foreign countries. The first lactic acid factory was established in Littleton, Massachusetts, in 1881 by Charles E. Avery.

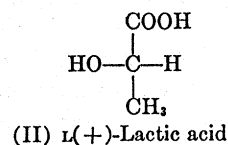
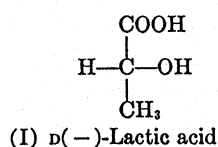
Many of the recent studies reflect a growing interest in the synthetic and industrial aspects of lactic acid chemistry and the transformation of abundant carbohydrates—through lactic acid as an intermediate—into various industrially valuable products, including chemical intermediates, solvents, plasticizers, and resins (12,31).

Physical and Chemical Properties

Structure and Physical Properties. Both optical isomers of lactic acid occur in nature, but the acid made commercially by fermentation is substantially the optically inactive form (19). The optically active acids have been prepared by fermentation under controlled conditions and by resolution of the racemic modification through the zinc ammonium salt or the salt with alkaloids such as morphine (1,13).

The literature is confusing regarding the designation of the isomeric forms of lactic acid, since *d*- and *l*- have been used to refer either to optical rotation or to

configuration. The acid commonly known as *sarcosolactic acid* or *paralactic acid*, the form occurring in blood, has a (+)-rotation but the L-configuration. It is, therefore, correctly designated L(+)-lactic acid (II) and its enantiomorph D(-)-lactic acid (I). The configurational relationships are shown in formulas (I) and (II). However, the



salts of the L(+)-acid are levorotatory, and the salts of the D(-)-acid are dextrorotatory. Lactic acid is usually obtained as a sirupy liquid; however, it can be obtained in pure crystalline form, though in low yield, by distillation at low pressures followed by crystallization. Table I shows some properties of the isomers (3). All three forms are hygroscopic, the racemic modification being more hygroscopic than the optically active isomers (3).

TABLE I. Properties of Lactic Acid Isomers.

Lactic acid	M.p., °C.	$[\alpha]_D^{25}$	Dissociation constant at 25°C.
D(-)-	52.8	2.6	—
L(+)-	52.8	-2.6	—
DL-	16.8	Inactive	1.38×10^{-4}

Because of the ease with which lactic acid undergoes self-esterification (see p. 169) when heated, it is difficult to determine the boiling point at most pressures, and im-

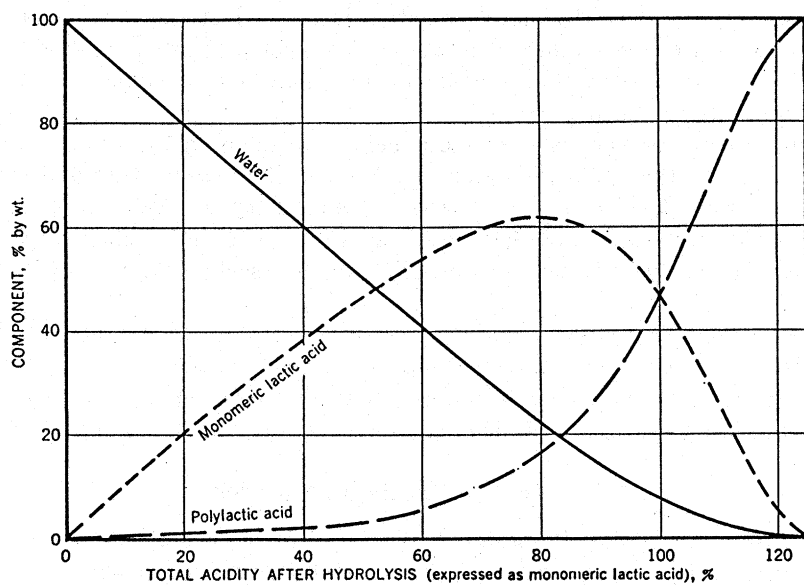


Fig. 1. Composition of lactic acid - water systems (9).

possible at atmospheric pressure. As calculated by the method of Kinney, the boiling point of lactic acid at atmospheric pressure is approximately 190°C. Investigators

have reported the following boiling points at reduced pressure: 119°C. at 12 mm. and 82–85°C. at about 1 mm.

The properties of aqueous solutions of lactic acid are particularly important since the acid is usually encountered in such solutions. The composition of dilute solutions, containing less than approximately 20% lactic acid, corresponds essentially to monomeric lactic acid and water. The solutions of higher concentration, however, are more complex because of self-esterification to so-called polylactic acids of various chain lengths. The equilibrium composition of aqueous lactic acid then depends on the concentration (2,13,29), and this relationship is shown in Figure 1.

The absolute viscosity of aqueous lactic acid (presumably DL-) has been reported, and the data are shown in Table II (27).

TABLE II. Viscosity and Density of Aqueous Lactic Acid at 25°C.

Lactic acid concn., %	Viscosity, centipoises	Density, g./ml.	Lactic acid concn., %	Viscosity, centipoises	Density, g./ml.
0	0.89	—	64.89	6.96	1.1518
9.16	1.15	1.0181	75.33	13.03	1.1748
24.35	1.67	1.0545	85.32	28.50	1.1948
45.48	3.09	1.1054			

The heat of combustion for lactic acid is 3615 cal./gram and the specific gravity 1.2060₄²⁵. Lactic acid is extremely soluble in water and in water-miscible organic solvents such as alcohol and acetone.

The distribution of lactic acid between water and numerous water-immiscible organic solvents has been reported. The results obtained by studying dilute (2–10%) aqueous lactic acid solutions are summarized in Table III (17). In general, the alcohols were most effective in extracting lactic acid.

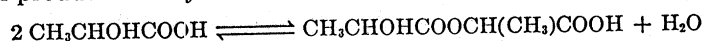
TABLE III. Distribution of Lactic Acid Between Water and Various Solvents.^a

Solvent	C_w	K	Solvent	C_w	K
<i>n</i> -Butyl alcohol	1.34	1.37	Ethyl acetate	1.77	4.07
Isobutyl alcohol	1.41	1.60	<i>n</i> -Butyl acetate	2.00	8.2
<i>n</i> -Amyl alcohol	1.65	2.45	Cyclohexyl acetate	2.08	13.0
Isoamyl alcohol	1.59	2.22	Ethyl carbonate	2.12	21.0
Benzyl alcohol	1.63	2.33	<i>n</i> -Butyl lactate	2.56	1.88
Cyclohexanol	2.60	1.74	Methyl isobutyl ketone	3.55	7.9
Ethyl ether	1.88	9.8	Diisobutyl ketone	2.22	36.0
Isopropyl ether	2.27	35	Mesityl oxide	1.84	3.76
Chloroform	1.87	100	Cyclohexanone	2.26	1.87
Nitroethane	1.81	11.0	Furfural	1.84	3.32
Pinene	1.87	80			

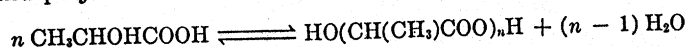
^a $K = C_w/C_s$; C_w = concn. in water phase; C_s = concn. in solvent phase.

Reactions. Lactic acid, by virtue of its hydroxyl and carboxyl functional groups, undergoes self-esterification when heated, forming linear polyesters as well as lactide, $\text{CH}_3\text{CH}(\text{COO})_n\text{CH}(\text{COO})_n\text{CH}_3$. When dilute aqueous lactic acid is concentrated by

distillation, the removal of water is accompanied by self-esterification. The first esterification product is lactyllactic acid:

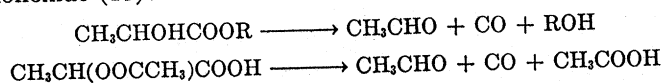


However, as the concentration proceeds, lactide and higher linear esters, that is the so-called polylactic acids (referred to in earlier literature as "anhydrides") or trimeric, tetrameric, and polymeric lactic acids, are formed (2,9,13,29):

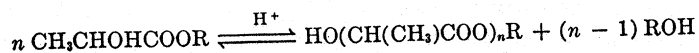


Equilibrium between these several components is attained slowly (several weeks) at room temperature. The linear polymer predominates; however, lactide, though originally present to the extent of a few per cent, is reportedly formed in good yields when the partly self-esterified mixture is distilled under reduced pressure. When lactic acid is pyrolyzed, it undergoes decomposition to acetaldehyde, carbon monoxide, and water. These two reactions occur, but at lower temperatures, when lactic acid is heated in the presence of mineral acids. With catalytic amounts of mineral acid, polylactic acid is formed, whereas, with larger amounts of mineral acid, decomposition into acetaldehyde, carbon monoxide, formic acid, and water takes place (13).

The monoesters of lactic acid when pyrolyzed also decompose into acetaldehyde and carbon monoxide (13):

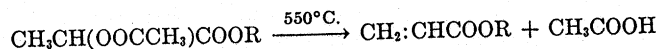


Under milder conditions, particularly in the presence of a mineral acid catalyst, the lactic esters undergo self-alcoholysis to produce esters of polylactic acid (13):



In these reactions, the lactic esters exhibit a behavior similar to lactic acid itself.

The diesters of lactic acid, however, show a completely different behavior when subjected to pyrolysis, acrylic esters and acetic acid being formed from acetylated lactic esters (4,13,25):



The yield of acrylic ester is markedly dependent on the structure of the alcohol radical R. When R is a thermally stable group that is not itself capable of forming an olefin, the yields of acrylic ester are high.

Lactic acid shows the typical reactions of organic acids. Many salts of this acid have been reported, and they are generally water-soluble. Lactic acid undergoes esterification readily with many alcohols and numerous lactic esters have been prepared by acid-catalyzed esterification. The esterification is complicated by the fact that esters of polylactic acid are simultaneously produced. The formation of esters of polylactic acid can be minimized by using an excess of alcohol in the esterification. It is necessary to neutralize the esterification catalyst with a base, such as sodium acetate, after the esterification is completed, in order to prevent self-alcoholysis of the lactic ester during isolation by distillation. It is preferable to distill the lactic ester at reduced pressure. The conversion of lactic acid to ester is usually quite good. Since the by-products, esters of polylactic acid, are actually a source of lactic acid, they may be recycled and the ultimate yield of lactic ester is usually high. The equilibrium constant for the esterification of lactic acid with ethyl alcohol is 2.71 ± 0.06 .

Lactic esters hydrolyze more readily than esters of the fatty acids, such as acetic acid, but less readily than esters of glycolic acid. The lactic esters of secondary alcohols, however, are in general considerably more resistant to hydrolysis than the esters

of corresponding primary alcohols (13). Lactic esters and lactide undergo alcoholysis readily with various alcohols. It is interesting that alcoholysis of lactide in the presence of a trace of catalyst produces esters of lactyllactic acid (34), whereas larger amounts of catalyst yield the monomeric lactic ester. An excellent method for preparing lactic esters is alcoholysis of methyl lactate with a higher alcohol.

Salts of lactic acid with primary and secondary amines can be dehydrated to the substituted lactamides. Lactamide, $\text{CH}_3\text{CHOHCONH}_2$, and substituted lactamides can also be prepared readily by ammonolysis or aminolysis of methyl lactate (see p. 179).

Lactic acid also shows many of the reactions characteristic of alcohols. Thus it can be esterified with organic acids, anhydrides, and acid chlorides. It can be alkylated with alkylating agents such as diazomethane and dimethyl sulfate. Lactic acid or its esters can be converted into chloroformates with phosgene, into carbamates with cyanic acid, and into allophanates and urethans with isocyanates (all typical alcohol derivatives). Lactic esters undergo dehydrogenation to the corresponding pyruvic ester, and can be converted into esters of inorganic acids by treatment with phosphorus oxychloride and thionyl chloride (13).

In addition to self-esterification, lactic acid shows some reactions involving the simultaneous participation of both the hydroxyl and carboxyl groups. With aldehydes and ketones, a cyclic acetal type of compound is formed (13). The aldehyde reaction product has the structure $\text{CH}_3\text{CH}.\text{CO}.\text{O}.\text{CH}(\text{R}).\text{O}$. Alkyl lactates react with urea forming 5-methyl-2,4-oxazolidinedione, $\text{CH}_3\text{CH}.\text{CO}.\text{NH}.\text{CO}.\text{O}$. This same compound is produced by interaction of lactamide with methyl carbonate. When an alkyl lactate is treated with guanidine, an analogous compound, 2-imino-5-methyl-4-oxazolidone, is formed (13).

Occurrence

Lactic acid in one or another of its three forms occurs extensively in nature. It is the principal acid constituent of sour milk, and a normal constituent in the blood and muscle tissue of animals. Abnormally high lactic acid values in human blood have been observed in pneumonia, tuberculosis, and heart failure. Lactic acid is a very important compound in biochemistry; the energy necessary for muscular action appears to be normally supplied by the conversion of glycogen, through a complicated series of reactions, into lactic acid. Lactic acid has been identified in yeast fermentation and is present in corn steep liquor, a by-product of the corn processing industry. Lactic acid is also found in such food products as sauerkraut, pickles, beer, butter-milk, and cheese (19,31).

Manufacture

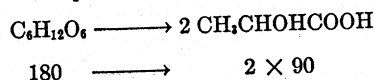
Although various methods of preparing lactic acid synthetically have been described, lactic acid is manufactured in the U.S. by fermentation, which produces essentially the optically inactive racemic form. The raw materials commonly used are molasses, starch hydrolyzates, or whey (see Vol. 5, p. 843) (6,15,19). Various other raw materials, including Jerusalem artichokes, grapefruit juice, corncobs, sulfite waste liquor, potatoes, and starch by-products, have also been investigated for this

purpose. The manufacture of various grades of lactic acid, as described by Peckham (19), is given below.

FERMENTATION

Several strains of *Lactobacillus* can be used for the fermentation, and some of the molds are adaptable (see Vol. 6, p. 363). The procedure in general consists in the fermentation of a carbohydrate together with suitable mineral and proteinaceous nutrients and an excess of calcium carbonate. It is generally preferred to use thermophilic bacteria of the *delbrueckii* type, which exhibit their optimum activity at 50°C. Such a fermentation eliminates most contamination problems and permits the use of a growing medium that has been pasteurized, as opposed to the sterilized growing media usually required for mesophilic fermentation. The lactic acid as formed is neutralized by the calcium carbonate, producing calcium lactate and carbon dioxide, preventing the pH from becoming low enough to inhibit fermentation. The fermentation liquor contains approximately 15% calcium lactate. Recent publications describe the laboratory fermentation of wheat grits and dextrose, employing continuous pH control with ammonia, ammonium carbonate, and sodium carbonate.

The theoretical yield of lactic acid is 100% of the weight of fermentable hexose sugar according to the overall equation:



In actual practice, this yield is never obtained. Presumably a portion of the carbohydrate is utilized by the organism in its metabolism. Further losses occur during subsequent processing, so that in commercial practice yields of about 85% are considered normal.

The technology of the recovery of lactic acid from the fermentation liquor varies considerably, depending on the grade of acid desired (19).

Crude lactic acid may be made by the direct acidification of the fermentation liquor obtained from a relatively impure carbohydrate substrate. The quantity and nature of the impurities in the final acid will depend upon the initial substrate as well as the method of manufacture and degree of refining (19).

Edible (or Food-Processing) Lactic Acid. Two methods are in use for the manufacture of edible lactic acid. In one the sugar is refined, and in the other the lactate or lactic acid is refined. In the first the fermentation mash is composed of highly refined sugar, a minimum of nutrient material, and a relatively pure calcium carbonate. After the fermentation is completed, the mash is acidified with sulfuric acid and the calcium sulfate removed by filtration. The light-colored lactic acid is then concentrated and refined by treatment with vegetable carbon. If necessary, iron and copper are removed by precipitation as the ferrocyanides by adding the stoichiometrical quantity of sodium or calcium ferrocyanide. The carbon and heavy-metal ferrocyanides are removed by filtration, and the lactic acid is diluted to the proper strength (19).

In the second type of process an inexpensive carbohydrate substrate is fermented. The calcium lactate liquor resulting from the fermentation may be clarified by filtration and concentrated to approximately 25% at the elevated temperature of evaporation. This solution is then cooled, whereupon the calcium lactate crystallizes. The crystalline product is separated by filtration or centrifugation, then redissolved in

water and acidified with sulfuric acid. The calcium sulfate is removed by filtration, and the resulting light-colored lactic acid concentrated to the proper strength (19).

An alternative procedure described by Jenemann (32) involves the extraction of lactic acid from the crude solution by isopropyl ether, followed by re-extraction of the lactic acid from the isopropyl ether with water. In this process concentrated crude lactic acid solution is continuously fed into the top of an extraction tower, while isopropyl ether is introduced at the bottom. The isopropyl ether solution of lactic acid is removed from the top of the tower and pumped into a second extraction tower. Here it is passed upwards through a countercurrent of water, which removes the lactic acid from the isopropyl ether. The purified aqueous solution of lactic acid is withdrawn at the bottom of the second tower, and the isopropyl ether is pumped from the top of this tower into the bottom of the first tower for further extraction of the crude lactic acid solution. This process results in somewhat higher purity acid than is required for edible grade, and the lactic acid made by this process frequently enters the market as plastic-grade lactic acid having a very low concentration of impurities, particularly ash (19,31).

U.S.P. XIV (formerly N.F.) Lactic Acid. There are three basic procedures available for the production of U.S.P. lactic acid. The solvent-extraction process outlined above may result in this grade of acid. A second, and one of the oldest, procedures is distillation with steam under relatively high vacuum. This is expensive, mainly because the relatively high boiling point of lactic acid results in self-esterification to nonvolatile polyesters. One purpose of the steam in this distillation procedure is to minimize this self-esterification. In this process the efficiency in overcoming entrainment is important. In usual practice the vapors are led to a partial condenser, which strips the bulk of distilled acid from the vapors resulting in a condensate of aqueous lactic acid, 50% or higher in concentration. Acid remaining in the vapor stream beyond the dephlegmator is recovered by concentration of the final condensate (19).

Perhaps the most practical method for production of this grade of lactic acid involves the formation of the methyl ester as an intermediate (10,11,33). Lactic acid is first dehydrated to a solution of high acid content, and this is subsequently esterified with methanol. The esterification may be carried out by refluxing the mixture in the presence of sulfuric acid catalyst, or it may be accomplished by passing methanol vapor through the acidified lactic acid at approximately 100°C. The latter method gives higher yields of methyl lactate, since the equilibrium is favorably displaced by removal of volatile methyl lactate (in the vapor stream) from the reaction. The methyl lactate may or may not be fractionated and then hydrolyzed completely by boiling in an excess of water with continuous removal of regenerated methanol. The residual aqueous solution from this treatment is the U.S.P.-grade lactic acid, and it requires some concentration to the final composition.

SYNTHESIS

Lactic acid can be synthesized by purely chemical methods that include degradation of sugars with alkalies such as lime and sodium hydroxide, interaction of acetaldehyde and carbon monoxide at elevated temperature and pressure (19), hydrolysis of acetaldehyde cyanohydrin (prepared from acetaldehyde and hydrogen cyanide), and hydrolysis of α -chloropropionic acid (prepared by chlorination of propionic acid). Synthetic methods, however, are generally more expensive than fermentation and for this reason are not widely employed at present.

MATERIALS OF CONSTRUCTION

Corrosion is one of the major problems encountered in the manufacture, storage, and shipment of lactic acid, particularly in the case of heat-transfer surfaces. Iron, steel, chrome steel, Monel, copper, and copper alloys exhibit poor resistance to aqueous lactic acid. Fairly resistant metals include nickel, Inconel, and low-iron alloys containing high percentages of nickel and chromium. Silver and tantalum resist corrosion by lactic acid, but are expensive. Ceramic materials, especially glass, are resistant, but their low coefficients of heat transfer and their brittleness limit their value in processing equipment. Wood is fairly suitable for use with dilute lactic acid, but the concentrated acid dries out the wood to a point where the joints are no longer tight (19,31).

Economic Aspects

Production in the U.S. was more than 1,000,000 lb. (on the basis of 100% acid) in 1917, when there were six manufacturers. It has increased greatly since this period and reached a peak of 8,619,000 lb. in 1944. Production of technical and edible lactic acid, which comprise the major portion of the lactic acid trade, and average sales prices, are shown in Table IV, as reported by the U.S. Tariff Commission.

Total imports of lactic acid were large until 1935, having fluctuated between 257,000 and 503,000 lb. annually (on 100% basis) for at least ten years. Since then, imports declined from 90,560 lb. in 1935 to 370 (100% basis) in 1941, when they ceased. Until 1938, Germany was the principal source of imports of all strengths of lactic acid. The small imports entered during the period 1938-41 were virtually all supplied by Japan. In the two decades 1928-48, the edible and medicinal grades accounted for the major portion of the annual total imports. Recently (1950) a small amount has been imported from the Netherlands.

TABLE IV. U.S. Production of Lactic Acid (100% Basis).

Year	Technical, 1000 lb.	Edible and medicinal, 1000 lb.	Total, 1000 lb.	Average price, ¢/lb.	
				Technical	Edible
1939	1530	1609	3139	12	21
1940	1671	1492	3163	13	21
1941	2646	2334	4980	13	22
1942	2931	3124	6055	15	24
1943	3242	4243	7485	16	25
1944	4458	4161	8619	14	23
1945	3467	4672	8139	16	26
1946	2219	3824	6043	15	29
1947	2525	3803	6328	18	33
1948	2316	2676	4992	20	36
1949	1700	2838	4538	23	39

In addition to lactic acid, the following derivatives (see p. 177) are commercially available in the U.S.: methyl, ethyl, *n*-butyl, calcium, sodium, antimony, copper, iron, and strontium lactates. Production data for these derivatives, except sodium lactate, are not available.

Grades and Shipping. Lactic acid is at present marketed in the following grades (6), in order of increasing quality: (1) crude, technical or commercial; (2) edible;

(3) plastic; and (4) U.S.P. The technical grade is sold in aqueous solution at 22%, 44%, 66%, and 80% concentrations. The buyer usually has some specification with regard to color or clarity, but of prime importance is that the calcium and sulfate ions be in chemical balance. The amount of free sulfuric acid must be negligible (19,31).

Lactic acid in aqueous solution is sold commercially in oak, cypress, or pitch pine wooden or paraffin-lined barrels, or in lined tank cars. The better grades are sold in glass-lined tank cars or in carboys. The prices of various grades of lactic acid as well as some of its derivatives are shown in Table V.

TABLE V. Price Quotations of Lactic Acid and Its Derivatives.

Grade	Concn., %	Price, ¢/lb.	
		As sold	100% basis
Lactic acid:			
Technical.....	22	5.8	26.4
	44	10.95	24.9
Edible.....	50	18.5	37.0
	80	28.5	37.0
Plastic.....	50	19.75	39.5
	80	35.0	43.8
N.F. ^a	85	69	81.2
Sodium lactate:			
Technical.....	50	13	26
Edible.....	50	19	38
	60	24	40
Calcium lactate, U.S.P.....	—	37	37
Methyl lactate.....	—	35	35
Ethyl lactate.....	—	41	41
n-Butyl lactate.....	—	41	41

Source: *Oil, Paint and Drug Reporter*, 158, No. 1 (July 3, 1950).

^a This grade, which was official in N.F. VIII, is now official in U.S.P. XIV.

A comprehensive cost analysis for the production of a 50% plastic-grade lactic acid and of methyl lactate has been recently published (18). The technology of lactic acid production has now been worked out to the point where it is possible to produce any quality required by the market. Further technological developments will be chiefly in the direction of reduced cost, which will in turn be dependent upon new advances in technology and perhaps more so upon increased industrial utilization. The present uses for lactic acid appear to be limited and comparatively small. Any notable increase in the utilization of lactic acid would most likely be in the plastics field.

Analysis

The standard method for the determination of lactic acid is that described by Friedemann and Graesser (14). The method involves the carefully controlled oxidation of lactic acid with potassium permanganate to form acetaldehyde. The acetaldehyde is swept from the oxidation mixture and absorbed in sodium bisulfite. The bisulfite solution is then titrated iodometrically. The acid strength of commercially available lactic acids is frequently determined by simple acid-base titration. Since polylactic acids are present in lactic acid, it is necessary to saponify them to determine the total available lactic acid.

These methods obviously do not distinguish the optically active forms of lactic acid. Because of the low rotatory power of optically active lactic acid, rotation is not a completely suitable indication of the optical form of the acid or of the percentage composition of a mixture. The benzimidazole derivative of lactic acid has a greater rotatory power, so that either form of lactic acid or the percentage composition of a mixture can be identified readily through the benzimidazole derivative.

Possible contaminants of the refined grades of lactic acid and their limits are: ash, 0.1%; heavy metals, 10 p.p.m.; chloride, sulfate, sugar, and other organic acids, no turbidity by the U.S.P. or N.F. test.

Uses

The uses of lactic acid can be divided into two categories: food and nonfood. In general lactic acid can be used as an acidulant in any kind of food or beverage. The following properties of lactic acid make it suitable in a variety of food products: (1) it has a mild acid taste in contrast to the sharp biting taste of other food acids; (2) it does not mask or overpower other flavors; (3) in some foods it prevents deterioration; and (4) it is in liquid form and ready for use. One or more of these properties have contributed to the increasing use of edible-grade lactic acid in animal food and remedies, bakery products, beer, butter, candy, cheese, dried egg whites, flavoring extracts, jelly, liquid pectin, mincemeat, olives, pickles, sauerkraut, soft drinks, soups, and sherbets.

Lactic acid has been reported to be an effective air-borne bactericide. A new germicide, containing *n*-dodecylamine lactate and *n*-dodecylamine salicylate, is currently being test-marketed as a disinfectant, antiseptic, fungicide, and mildew-proofing agent.

Crude lactic acid has long been in use in the leather industry for deliming hides, for bating and plumping sole leather, and in vegetable tanning. It is also the raw material for preparing the esters such as methyl, ethyl, and *n*-butyl lactates, which are of use as solvents. Use is also made of this grade in the acid dyeing of wool and other textiles. Other nonfood uses include applications such as adhesives, cleaning and polishing formulations, electroplating and electropolishing, insecticides and fungicides, lithographic developers, oil and water well treating, plastics and resins, special inks and textiles. In the manufacture of phenol-formaldehyde resins, lactic acid is useful in neutralizing the alkali catalyst, since a noncrystallizable salt is formed, which does not impair the clarity and strength of the resin. A high-purity lactic acid, essentially free of iron, is desired in this application.

An estimate of the end uses (per cent of the total) of lactic acid in various industries was reported for 1942 (see Table VI) (24).

TABLE VI. End Uses of Lactic Acid in 1942.

Use	Per cent of total	Use	Per cent of total
Tanning.....	37.4	Plastics.....	1.2
Jobbers—chemical, etc.....	17.3	Pickles.....	1.1
Export.....	30.0	Brewing.....	1.1
Jams, jellies, and preserves.....	7.6	Soft drinks.....	0.8
Olives.....	1.6	Confectionery.....	0.2
Dyeing.....	1.3	Miscellaneous.....	0.4

Publications have appeared in recent years indicating new potential applications of lactic acid and its derivatives. Thus, the use of lactic acid as an extender for glycerol in alkyd resins (26) has been described. The preparation of coatings by reaction of polylactic acid with drying oils or with small amounts (1-6%) of salts of polyvalent metals such as aluminum, chromium, cobalt, copper, iron, lead, manganese, thorium, tin, titanium, and zinc has been reported (30). The addition of dicyclopentadiene to lactic acid (36) results in a dihydrodicyclopentadienyl ether-ester of lactic acid, which rapidly absorbs oxygen from air, especially in the presence of driers, to give an insoluble varnish-like film, behaving in this respect like drying oils. This ether-ester can also be polymerized by heating with peroxides to a viscous autoxidizable oil. Many high-boiling lactic esters have been evaluated in a preliminary manner as plasticizers for resins (8,12,22,23). Mixed esters of lactic and adipic acid of the types $\text{ROOC}(\text{CH}_2)_4\text{COOCH}(\text{CH}_3)\text{COOR}$ and $(\text{CH}_2\text{CH}_2\text{COOCH}(\text{CH}_3)\text{COOR})_2$ have been shown to be efficient plasticizers for vinyl chloride copolymers (22). Mixtures of such esters were prepared by esterification of an alkyl lactate with adipic acid (or other dibasic acid such as sebacic acid). Lactic acid or methyl lactate when used with an alkanol was equivalent to the alkyl lactate in this esterification (22). Lactic acid can be smoothly converted into methyl acrylate by the following sequence of reactions: conversion to methyl lactate, acetylation, and pyrolysis at 550°C. (4,25).

Derivatives

SALTS

Of the commercially available salts of lactic acid (calcium, sodium, antimony, copper, iron, and strontium), calcium and sodium lactates are most important and may be prepared as the primary fermentation product by control of the pH during fermentation through the use of calcium carbonate or sodium carbonate, respectively. The salts of lactic acid can also be prepared by neutralization of the acid with metal carbonates or hydroxides.

Calcium lactate, $(\text{CH}_3\text{CHOHCOO})_2\text{Ca} \cdot 5\text{H}_2\text{O}$, formula weight 308.3, crystallizes as the pentahydrate, which is slightly efflorescent and loses water of hydration at 100-120°C. The hydrate is soluble in 100 grams of water to the extent of 3.1, 5.4, and 7.9 grams at 0°, 15°, and 30°C., respectively, but it is miscible in hot water. Calcium lactate is widely used in calcium therapy and has been employed as a blood coagulant in treatment of hemorrhages. Sugar solutions can be jellied by the addition of cal-

TABLE VII. Properties of Aqueous Sodium Lactate Solutions.

Concn., wt. %	d_4^{25}	n_D^{25}	Viscosity at 25°C., millipoises	Surface tension at 29°C., dynes/cm.
0	0.9971	1.3329	8.94	71.4
1	1.0042	1.3348	9.29	70.4
2	1.0074	1.3356	9.60	—
5	1.0225	1.3400	10.60	—
10	1.0480	1.3473	12.40	69.6
20	1.1002	1.3623	20.38	—
30	1.1542	1.3778	36.38	68.5
40	1.2078	1.3929	72.91	64.8
50	1.2629	1.4078	179.79	45.5
60	1.3131	1.4209	550.63	56.7
70	1.3717	1.4353	3798.5	60.7
77.2	1.4085	1.4440	—	—

cium lactate. This salt has been described as a desirable agent for the firming of apples.

Sodium lactate, $\text{CH}_3\text{CHOHCOONa}$, formula weight 112.1, is sold in aqueous solution as the 50% technical, 50% edible, and 60% edible grades. Properties of aqueous sodium lactate are given in Table VII (5). It is difficult to obtain the crystalline salt, which is very hygroscopic and highly soluble in water (5) and in alcohol. The production of sodium lactate in the U.S., as reported by the U.S. Tariff Commission, is shown in Table VIII. Sodium lactate, being hygroscopic, has been used as a glycerol substitute, for example, as a plasticizer and humectant in paper and textiles.

TABLE VIII. U.S. Production of Sodium Lactate.

Year	Production, lb. (100% basis)	Av. price, ¢/lb. (100% basis)	Year	Production, lb. (100% basis)	Av. price, ¢/lb. (100% basis)
1944.	324,000.	19	1947.	556,000.	27
1945.	143,000.	24	1948.	172,000.	35
1946.	369,000.	30	1949.	220,000.	23

Other Salts. *Aluminum lactate*, $(\text{CH}_3\text{CHOHCOO})_3\text{Al}$, a granular solid freely soluble in water, is of use as an antiperspirant. *Antimony lactate*, $(\text{CH}_3\text{CHOHCOO})_3\text{Sb}$, is used in mordant dyeing of textiles. *Copper lactate*, $(\text{CH}_3\text{CHOHCOO})_2\text{Cu} \cdot 3\text{H}_2\text{O}$, which is soluble in water, can be used in electroplating baths. *Iron lactate* (ferrous lactate), $(\text{CH}_3\text{CHOHCOO})_2\text{Fe} \cdot 3\text{H}_2\text{O}$, which is soluble in water, is used for treatment of anemia and as an ingredient of tonics and an infant food. *Strontium lactate*, $(\text{CH}_3\text{CHOHCOO})_2\text{Sr} \cdot 3\text{H}_2\text{O}$, also finds use as a pharmaceutical.

ESTERS

Conventional esterification processes are used for the commercial production of methyl, ethyl, and *n*-butyl lactates, and the yields are high (see Vol. 5, p. 813). Lactic acid is the usual starting material; however, salts of lactic acid, from which the acid is liberated by mineral acids (35), may also be used. In the case of methyl lactate, polylactic acid is a more desirable intermediate than lactic acid, the ester being formed in part by esterification and in part by alcoholysis reactions (11,33). By this method, the problem of separating methyl lactate from water can be practically eliminated by using polylactic acid of moderately high degree of polymerization. Ethyl lactate is prepared not only from fermentation lactic acid, but synthetically as well. The latter process utilizes acetaldehyde cyanohydrin, which on interaction with ethyl alcohol yields ethyl lactate.

Many esters of lactic acid have been reported in the literature. Some of these are high-boiling liquids with properties of interest as plasticizers for cellulose plastics and vinyl resins (8,12,22,23). Many azeotropes of methyl and ethyl lactate have been reported (16).

Hydrolysis of lactic esters has received much study. In general, the rate of hydrolysis of esters of organic acids is roughly proportional to the strength of the organic acid. Lactic esters are hydrolyzed more rapidly than the corresponding propionic esters. The rate of alkaline hydrolysis (saponification) of *n*-alkyl lactates decreases as the size of the alkyl group increases, the most pronounced difference in rate being between methyl and ethyl. The rate of acid-catalyzed hydrolysis of *n*-

alkyl lactates through butyl is virtually independent of the alkyl group, and the same is substantially the case in uncatalyzed hydrolysis. Lactic esters of secondary alcohols are considerably more resistant to hydrolysis than those of the corresponding primary alcohols (13).

Methyl, ethyl, and butyl lactates are easily acetylated with acetic anhydride to produce the acetyl derivatives, which are slightly soluble in water and boil approximately 25°C. higher than the corresponding lactic ester.

Methyl lactate, $\text{CH}_3\text{CHOHCOOCH}_3$, formula weight 104.10, m.p. -66°C ., b.p. 145°C ., b_{10} 42°C ., d_4^{20} 1.0939, n_D^{20} 1.4139, viscosity 2.94 centipoises at 20°C ., is miscible with water, distilling as an azeotrope (about 25% ester, b.p. 99°C .). It is in many respects a potentially important and key derivative of lactic acid. The lactic esters of higher alcohols can be readily prepared by alcoholysis of methyl lactate with the appropriate alcohol. Furthermore, the removal of lactic acid from the crude as the methyl ester promises to be the most practical method for purifying lactic acid. Methyl lactate also is the key intermediate in the conversion of lactic acid into acrylic esters; this process, though not commercially practiced in the U.S., is used on a small scale in at least one country. Methyl lactate can be acetylated with acetic acid to produce either methyl α -acetoxypionate or α -acetoxypionic acid as the predominant product (7). Methyl lactate is considerably more reactive than the higher alkyl lactates in ammonolysis.

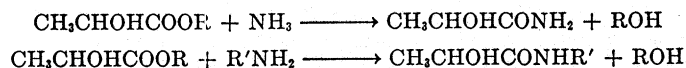
The kinetics of the esterification of 85% and 44% lactic acid with methanol have been reported (28). The reaction is not a simple first-, second-, or third-order reaction. The effect of temperature, concentration of mineral acid catalyst, and mole ratio of reactants was also studied.

Ethyl lactate, $\text{CH}_3\text{CHOHCOOCH}_2\text{CH}_3$, formula weight 118.13, m.p. -25°C ., b.p. 154°C ., b_{10} 51°C ., d_4^{20} 1.0348, n_D^{20} 1.4132, viscosity 2.61 centipoises at 20°C ., is miscible with water. The lactic esters of higher alcohols can be readily prepared by alcoholysis of ethyl lactate with the appropriate alcohol. Ethyl lactate also may serve as a volatile ester of lactic acid for the purification of the acid. Ethyl lactate is used in solvents for lacquers and has also found use as a lubricant in the manufacture of tablets.

n-Butyl lactate, $\text{CH}_3\text{CHOHCOO}(\text{CH}_2)_3\text{CH}_3$, formula weight 146.18, m.p. -43°C ., b.p. 187°C ., b_{10} 75°C ., d_4^{20} 0.9837, n_D^{20} 1.4217, vapor pressure 0.4 mm. Hg at 20°C ., viscosity 3.58 centipoises at 20°C ., surface tension 30.6 dynes/cm. at 20°C ., flash point (Tag open cup) 168°F ., is soluble to the extent of 4.36 grams per 100 ml. of water at 25°C . Butyl lactate is used as a high-boiling solvent in lacquer formulations.

AMIDES

Amides of lactic acid, lactamides, are readily prepared by interaction of lactic esters with ammonia and amines:



The reactivity of lactic esters in ammonolysis is considerably greater than that of esters of unsubstituted aliphatic acids except formic acid. Methyl lactate is the most reactive lactic ester toward ammonolysis, the yield being almost quantitative. Many substituted lactamides have been prepared by aminolysis of methyl lactate. The primary alkylamines react readily and almost quantitatively at room temperature. The secondary amines, with a few exceptions, are not suitable in this reaction. The

notable exceptions are dimethylamine, morpholine, piperidine, pyrrolidine, and diethanolamine, which give very high yields (21).

The *N*-alkyl-substituted lactamides are in general low-melting solids of high boiling point. The lower members, methyl-, ethyl-, *n*-propyl-, and *n*-butyllactamide, are very soluble in water, whereas the higher members are slightly soluble in water (21). The *N*-hydroxyalkyl-substituted lactamides, for example, *N*-2-hydroxyethyl-, *N,N*-bis(2-hydroxyethyl)-, and *N*-2-hydroxypropyllactamide, are viscous water-soluble liquids, showing hygroscopic properties (20).

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